From interfaces to infrastructure

From interfaces to infrastructure: Extending ecological interface design to re-design rail level crossings

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Abstract

Collisions between trains and road vehicles at rail level crossings remain an intractable transport safety issue. This paper describes the application of Rasmussen's ecological interface design (EID) principles to the development of a novel 'passive' rail level crossing prototype design and its evaluation using two driving simulator studies. Study 1 involved the design of the prototype EID crossing. Study 2 compared the EID crossing design with a standard 'active' rail level crossing with red flashing lights under normal conditions and Study 3 compared the crossings under conditions of driver distraction and technology failure. The findings show that under normal conditions the EID crossing produced more cautious speed on approach than the standard design, but similar patterns of decision-making. Under conditions of distraction and failure, participants again demonstrated more cautious speed profiles on approach when encountering the EID design. Importantly, in technology failure conditions, the EID design appeared to encourage participants to engage in higher-level problem solving, which was not seen in response to the standard crossing. It is concluded that the EID crossing may be more able to support adaptive decision-making under conditions of failure or uncertainty.

Keywords

Ecological interface design, Driving simulation, Highway-rail grade crossings, Rail level crossings, Transportation safety

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1. INTRODUCTION

1.1 Rail level crossing safety

Collisions between road vehicles and trains at rail level crossings (alternatively known as grade crossings or rail-road crossings) remain a safety concern worldwide (e.g. ERA 2017; ONRSR 2016; ORR 2018). In a number of countries such as the USA, New Zealand and Australia, rail level crossings with ‘passive’ protection (i.e. with static signage instructing road users to stop or yield / give way to trains) present a particular risk as they do not provide a warning of approaching trains. It is generally accepted that providing ‘active’ warnings, such as flashing lights or boom barriers that activate to warn of a train approaching, is superior for reducing collisions (Saccomanno et al. 2007). However, the cost of installing such warnings can be prohibitive, as they rely on train detection and warning technologies that must meet high standards of reliability, including failing to a safe state (Wullems 2011). Cost is a particular issue in rural environments where electrical infrastructure is not available to power active warning devices. Lower cost technologies for providing warnings are being investigated (Wullems 2011), yet it may be possible to use fully passive solutions to create a similar safety advantage using applied ergonomics approaches rather than purely engineering ones. This paper presents aspects of a wider study into improving rail level crossing safety (Read et al. 2017; Salmon et al. 2016).

1.2 Rasmussen Remixed

A design approach pioneered by Rasmussen and colleagues (Vicente and Rasmussen, 1992) was applied in this research. Ecological interface design (EID) has been used with some success previously in transport domains (e.g. Young and Birrell 2012; McIlroy et al, 2017) and an opportunity exists in this study to rethink, re-mix and re-scale the way EID is used. The EID approach intends to support users in both familiar and unfamiliar situations, with emphasis on supporting users to make appropriate decisions in unanticipated situations (Vicente and Rasmussen 1992). This is achieved through making constraints explicit to end-users, typically via displays or control interfaces. EID is a "top-down" approach that bases design requirements on an understanding of the system constraints that limit behaviour, coupled with an understanding of human capabilities and limitations.

EID uses the Work Domain Analysis (WDA) phase of Cognitive Work Analysis to identify the constraints of the system of interest (Vicente and Rasmussen 1992). WDA, using the abstraction hierarchy representation, identifies the functional purpose/s and structure of the 'work domain' or system of interest (Rasmussen, 1986). Through a description of the system across five levels of abstraction, the ecological constraints associated with the system are identified. These can include causal or 'hard' constraints that have their basis in physical or natural law and therefore cannot be violated, as well as intentional or 'soft' constraints which stem from social laws, conventions or values. Soft constraints can be violated, although it would be socially unacceptable to do so (Burns, Bryant & Chalmers, 2005).

Having understood the system constraints using WDA, EID then employs Rasmussen's (1983) skill, rule, and knowledge (SRK) taxonomy to guide design. The SRK taxonomy proposes that people engage in three levels of information processing:

- Skill-based behaviour: Associated with sensory-motor performance and occurs in skilled activity without conscious control being required.
- Rule-based behaviour: Involving the application of stored rules, based on past experience, to determine an appropriate course of action.
- Knowledge-based behaviour: Engaged in unfamiliar situations where it is not possible to draw upon past experience and the individual must engage in effortful reasoning to understand the situation and determine an appropriate course of action.

Importantly, skill- and rule-based behaviours are based on immediate perception of a situation, whereas knowledge-based behaviour requires deeper analytical processing (McIlroy and Stanton

2015b). The principles of EID dictate that a design should support all three levels, but should not require the user to activate a higher level of cognitive control than is inherently demanded by the task. That is, an EID-based design should support direct perception and action, while also supporting analytical problem-solving required in non-routine situations in which the individual does not have a repertoire of skill-based responses or rules to apply.

The EID philosophy has been applied across diverse domains, such as aviation (Stanton and McIlroy, 2012), air traffic control (Borst et al. 2017), healthcare (Watson and Sanderson 2007), maritime (Morineau et al. 2009) and road (Young and Birrell 2012; McIlroy et al, 2017). Although there have been studies providing evidence that EID-based designs outperform traditional interfaces (e.g. Burns and Hajdukiewicz 2004; Vicente 2002), most reported uses of WDA in design do not provide evidence of evaluations of the designs produced. Further, previous applications of EID have focused on the design of human-machine interfaces (predominantly computer-based displays) but there is no inherent reason why the design approach cannot be applied to much larger environments, such as a rail level crossing environment. This paper tackles both gaps in the current literature, firstly, by increasing the scale of EID to design a novel rail level crossing environment and, secondly, evaluating its impact on driving performance when compared to a standard active rail level crossing.

1.3 Research approach

The paper describes a series of studies which developed, and then evaluated a novel EID-based design for rural rail level crossings. Study 1 involved a design process to generate the prototype EID crossing. Studies 2 and 3 evaluated driving performance and decision-making in response to the EID crossing using a driving simulator study, in comparison to a standard rail level crossing design. In Study 2 participants encountered the design under normal operating conditions. In Study 3 participants encountered the design under conditions of distraction and technology failure to determine how participants would respond to the design under these non-optimal conditions.

We measured performance in the driving simulator studies in two ways: 1) the mean speed of participants on approach to the crossing; and 2) participants decision-making on approach to the crossing, using participants concurrent verbal protocols ('thinking aloud') and Rasmussen's decision ladders (Rasmussen, Pejtersen, & Schmidt 1990; Vicente 1999). Verbal protocols are a commonly used means for describing and assessing decision making and situation awareness (e.g. Banks et al., 2014; Parnell et al., 2018; Salmon et al., 2014; Sanderson et al., 1989; Walker et al. 2011) and studies have demonstrated that there is no significant impact on driver behaviour while performing verbal protocols (Salmon et al., 2017). The decision ladder analysis enabled an analysis of the extent to which participants engaged in skill-, rule-, and knowledge-based behaviour under different conditions.

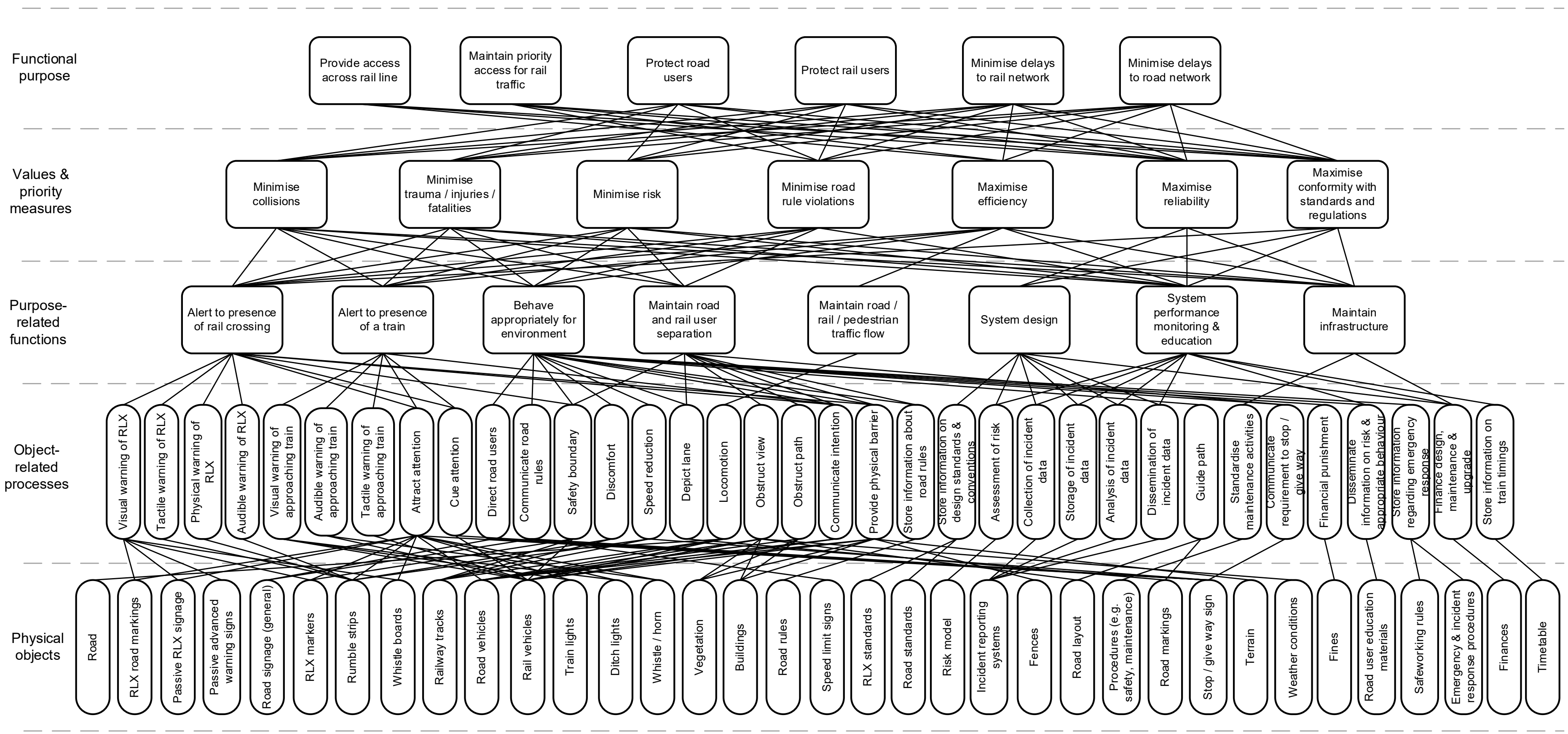
2. STUDY 1: APPLYING ECOLOGICAL INTERFACE DESIGN TO DEVELOP A NOVEL RAIL LEVEL CROSSING ENVIRONMENT

2.1 Method

The first step in generating the EID-based rail level crossing involved the development of an abstraction hierarchy within the WDA phase of Cognitive Work Analysis. This abstraction hierarchy (Figure 1) described the functional structure of a standard passive rail level crossing, in a rural road context. The abstraction hierarchy drew upon data collected from on-road studies of drivers at rural rail level crossings in Victoria, Australia (Salmon et al., 2013; Lenné et al., 2013; Beanland et al., 2017; Read et al. 2017), as well as discussions with train drivers and in-cab familiarisation rides undertaken by the researchers.

Following its development, the abstraction hierarchy was reviewed to identify the key constraints that influence the behaviour of end users at rail level crossings (i.e. road users and train drivers).

Figure 1. Abstraction hierarchy for passive rail level crossings. Note, RLX = rail level crossing.



The review was undertaken in a workshop setting, involving seven human factors researchers; five of whom had previously been involved in developing the abstraction hierarchy. Workshop participants undertook a structured review of the abstraction hierarchy to identify the key constraints on behaviour at rural rail level crossings. The experts were asked to identify the key constraints that influence the behaviour of various end users including car drivers, heavy vehicle drivers, cyclists, motorcyclists, pedestrians and train drivers.

Most of the key constraints identified related to the physical processes afforded by road and rail vehicles, given that the risk of collision is present when separation is not maintained between these users. An example constraint was the braking capacity of the train. Due to the large mass of trains it is difficult for them to stop in short distances, even under emergency braking (Stanton and Walker, 2011). This is an important constraint because it places all responsibility to prevent a collision on road users, and leaves little opportunity for the system to recover from situations where the road user fails to stop or give way to the train.

Once the key constraints were identified, experts were asked to analyse each constraint by considering a set of questions that sought to explore how constraints could be manipulated to reduce the risk of collisions. The questions explored whether constraints could be removed (following Stanton et al, 2013), could be strengthened, or if design could be improved to make the constraints more visible or explicit to users. Table 1 provides a summary of the key constraint analysis findings.

Table 1. Analysis of key constraints

Key constraint	What would happen if it was removed?	What would happen if it was strengthened?	How could constraints be made more visible / explicit?	Design solution
Train presence	If trains were removed the risk would be eliminated, but no functional purposes would be achieved.	Increasing the presence of trains could promote road users to behave appropriately for the environment (show caution), as they would be more likely to expect a train.	The visual appearance of the train could be modified to increase salience. The sound of the train / train horn and its visual appearance of the train could be re-directed from the periphery towards road user.	- Increase the salience of the train - Reflect the image of the train towards the road -Reflect the sound of the train horn towards the road
Train braking capacity	n/a	Braking capacity could be enhanced through technical intervention or slowing the speed of the train.	The visual appearance of the train could be used to demonstrate the speed / momentum of the vehicle.	- Visual appearance of the train also emphasises the speed of the train - Train speed is reduced through the crossing
Train speed	n/a	Braking or slowing by the road user could be encouraged by creating a perceptual illusion of faster movement. Train speed could also be lowered, to provide an opportunity for trains to slow / stop in an emergency.	Road user judgements of train speed could be improved by using guide posts.	- Guide posts down side of railway line
Road vehicle speed	n/a	Braking or slowing by the train driver could be encouraged by creating a perceptual illusion of faster movement.	Train driver judgements of road user speed could be improved by using guide posts.	- Guide posts down side of roadway

Key constraint	What would happen if it was removed?	What would happen if it was strengthened?	How could constraints be made more visible / explicit?	Design solution
Danger zone	Removing visual demarcation of the danger zone may cause confusion for road users. May result in them not being alerted to the presence of the crossing, and not behaving appropriately by stopping in a safe place if a train is approaching.	Strengthening the danger zone could promote road users to understand the danger posed by the environment and lead to more cautious approach and stopping behaviour. This could be achieved through the application of field of safe travel principles.	Strengthening the visual demarcation of the danger zone / field of safe travel could draw additional attention to the presence of the crossing and ensure that road users behave appropriately by reducing speed.	- 'Field of safe travel' road markings provided on road on crossing approach

The next step involved using the insights gained from the constraints analysis to design a novel rail level crossing environment. In line with the EID philosophy, the expert group were given the overall goal of developing a crossing design that supports adaptive capacity (i.e. flexibility, adaptability and resilience), and where the end user could be supported to 'finish the design'. To support this, the group was asked to consider Rasmussen's (1983) Skill, Rule and Knowledge framework. The group was also asked to consider whether Field of Safe Travel theory (Gibson and Crooks 1938) could be used to support the improved design of the rail level crossing environment. Field of safe travel theory posits that drivers operate by perceiving a dynamic space around their vehicle which, based on the surrounding traffic and hazards, is judged to be safe to occupy. Drivers seek to preserve an acceptable ratio between available stopping distance and the boundary of the perceived safe field ahead. In this design process the group was asked to consider how the field of safe travel could be used to make the key constraints visible to end users. Finally, the group were asked to consider how best to optimise trade-offs between the different values and priority measures identified in the abstraction hierarchy. For example, there is an inherent conflict between the value of safety and efficiency that must be managed, particularly in the context of rail level crossings where road users are required to stop or give way to approaching trains to maintain separation and avoid crashes, thus impacting on the efficiency of the road network.

2.2 Results

The resulting EID-based crossing design comprised a range of novel features (see Figure 2 for initial design representation). Each feature is discussed in the following sections.

2.2.1. Road markings

A coloured area is provided across the tracks to emphasize the danger zone, with coloured markings extending back along the approach road and forming a ‘tongue’ intended to represent a static field of safe travel that ends just prior to the crossing. This feature intends to support skill-based behaviour through immediate perception of safe and unsafe zones in the environment. It provides a new physical object in the environment which supports the object-related process of a ‘safety boundary’, which supports the function of ‘behave appropriately for the environment’, which in turn supports the functional purposes of ‘protect road users’ and ‘protect rail users’. The effectiveness of the road markings would be measured through the safety-related measures of ‘minimise collisions’, ‘minimise trauma / injuries / fatalities’ and ‘minimise risk’.

2.2.2. Guide posts

Posts are provided along both the road and railway tracks, with decreasing intervals on approach to the crossing, providing a reference point for road vehicle drivers and train drivers to judge the speed of the approaching traffic. The posts emphasize the constraint of speed by increasing self-perceived travel speed, supporting skill-based performance through influence non-conscious perception of one’s own speed. The guide posts represent a new physical object that supports the object-related process of ‘speed reduction’. This supports the purpose-related function of ‘behave appropriately for environment’, which in turn supports the functional purposes of ‘protect road users’ and ‘protect rail users’. The safety effectiveness of the guide posts would be measured through the safety-related measures of ‘minimise collisions’, ‘minimise trauma / injuries / fatalities’ and ‘minimise risk’. The guide posts could have a negative effect on the functional purpose of ‘minimise delays to road network', if the speed reduction was too strong, particularly when no train is approaching. The impact on delays to the road network would be measured through the measure of 'maximise efficiency'.

2.2.3. Reflectors

Large mirrors or reflecting devices are provided at the crossing which reflect the image of an approaching train to represent its relative distance, shifting this constraint from the track to the roadway directly in front of road users. The mirrors also reflect the sound of the train horn toward the roadway. The reflectors represent a new physical object that supports the object-related processes of 'visual warning of approaching train' and 'audible warning of approaching train'. These processes in turn support the function of 'alert to presence of a train' which supports the functional purposes of 'protect road users' and 'protect rail users'. The effectiveness of the reflectors would be measured through the safety-related measures of 'minimise collisions', 'minimise trauma / injuries / fatalities' and 'minimise risk'.

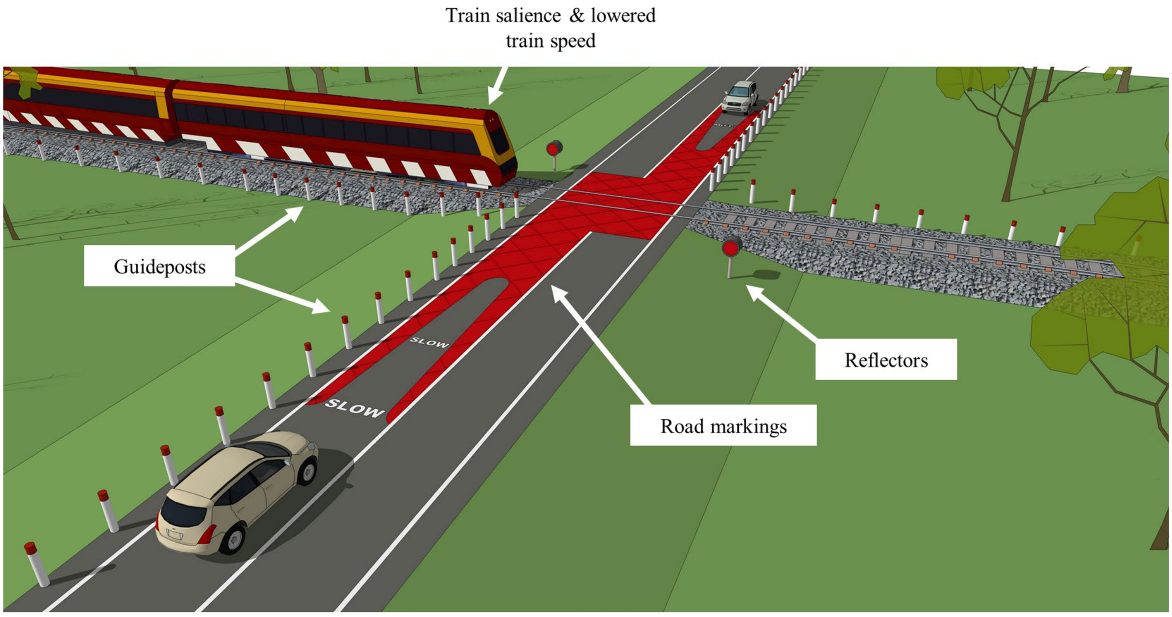
2.2.4. Train salience

The train's appearance is altered from a standard colour scheme to increase its visual salience. To highlight the danger posed by the train, the external paint scheme of the train is altered to imitate a character that exemplifies speed and strength (e.g., "Ironman") and a red-and-white striped segment is painted on the side of the train so that, when traversing a crossing, the train mimics a traditional boom barrier. This feature represents an enhanced existing physical object ('rail vehicles'). This will enhance the object-related process of 'visual warning of approaching train', 'attract attention', and 'safety boundary' (particularly with the representation of the boom barrier painted down the side of the train). These enhanced objects will support the purpose-related functions of 'Alert to presence of a train' and 'behave appropriately for environment', which in turn support the functional purposes, in particular those of 'protect road users' and 'protect rail users'. The extent to which the enhanced train salience is effective would be measured through the safety-related measures of ‘minimise collisions’, ‘minimise trauma / injuries / fatalities’ and ‘minimise risk’.

2.2.5. Lowered train speed

Train speed is slowed to 20 km/h (12 mph) through the crossing to provide the train driver with more control to stop if they perceive a potential collision with a road vehicle. Speed is a property of the existing physical object of ‘rail vehicles’, and the lowered train speed supports the existing object-related process of ‘speed reduction’, which in turn supports the purpose-related function of ‘behave appropriately for environment’. The lowered speed also contributes to the object-related process of ‘safety boundary’, as it enables more time for recovery within a collision scenario. in turn support the functional purposes, in particular those of ‘protect road users’ and ‘protect rail users’. The extent to which the lowered train speed is effective would be measured through the safety-related measures of ‘minimise collisions’, ‘minimise trauma / injuries / fatalities’ and ‘minimise risk’. The change could, however, have a negative effect on the functional purpose of ‘minimise delays to rail network’, particularly on railway lines with higher train speeds and many rail level crossings. The impact on delays to the rail network would be measured through the measure of ‘maximise efficiency’.

Figure 2. Initial design of the EID-based rail level crossing design



3. STUDY 2: EVALUATION UNDER NORMAL CONDITIONS

3.1 STUDY DESIGN

The EID design was evaluated with other novel designs, which were compared to two existing standard designs (one active, one passive). An overview analysis covering the two other designs, and comparing the EID design with the standard passive design, is provided in another publication (Beanland et al., 2018). This analysis focuses on a more in-depth comparison between EID and one existing standard design, using a within-subjects design whereby each participant experienced both the EID and standard active design.

Each crossing design was encountered multiple times both with and without a train present. The existing standard design was an 'active' crossing featuring flashing lights and bells but no boom barriers. At such crossings, drivers are required to stop if the flashing lights are activated, or to otherwise give way to any approaching train. It conformed to contemporary Australian design standards (AS 1742.7–2007) and was selected for comparison as the EID design could represent an alternative, lower cost option to upgrading from a passive crossing to flashing light warning systems, given that it does not require a power source to operate.

The simulations were designed to reflect the design, operation and context of rail level crossing in a rural environment in Victoria, Australia. In line with this, the default road speed limit was 100 km/h (62 mph), reduced to 80 km/h (50 mph) on approach to each rail level crossing, reflecting real-world conditions. All rail level crossings were situated on a straight stretch of road with good sight distance. Default train speed for the standard crossing was 80 km/h, with trains slowed to 20 km/h through the crossing in the EID design.

3.2 METHOD

3.2.1 Participants

Participants were 30 drivers (21 male) with an average of 14.8 years' driving experience (*SD* = 12.3). All participants were experienced, fully-licensed drivers who provided written informed consent and received financial reimbursement for their time. Ethical aspects of the research were approved by the University of the Sunshine Coast Human Research Ethics Committee (approval number A/15/756).

3.2.2 Apparatus

A medium-fidelity fixed-base driving simulator was used, comprising an adjustable driver's seat, automatic transmission, Logitech G27 vehicle controls (brake, accelerator, steering wheel), and three 40" LCD monitors representing a 135° field of view. The vehicle instrument panel was displayed on a 9.7" tablet screen. Oktal SCANeR™ studio v1.5 was used to program the scenarios and collect performance measures. Figure 3 shows screenshots of the standard active and EID designs, as experienced by participants.

A handheld tablet was used for the completion of participant questionnaires. A dictaphone was used to record participants' concurrent verbal protocols.

Figure 3. The standard active design and EID design. Note, the peripheral view available to participants is not shown.

3.2.3 Procedure

Prior to commencement of each study, participants were pre-screened to exclude those with a disposition to simulator sickness, given an overview of the research methods and provided written informed consent. Participants then completed a brief demographic questionnaire that collected information about their driving experience and habits. They were then asked to seat themselves comfortably in the driving simulator and received training in providing concurrent verbal protocols. Verbal protocols are used to gain insight into the cognitive and physical processes used by participants to perform a task (Walker 2005). This is achieved by asking participants to 'think aloud' while concurrently performing the task under analysis. As part of the training, participants viewed a video recording of a human factors expert providing a concurrent verbal protocol during while driving. The demonstration did not include any rail level crossings. Participants were then given examples and instructions to encourage them to focus on verbalizing cognitive processes (e.g., "I'm checking the speed sign") rather than physical actions (e.g., "I'm pressing the accelerator"). Next, participants undertook a familiarisation drive to gain experience with the simulator controls and to practice the verbal protocol procedure. The familiarisation drive took place in a rural setting (similar to the experimental drive scenarios) but did not include any rail level crossings. The experimenter was available to answer any questions and provided feedback on the verbal protocols provided. When participants felt confident they began the experimental tasks involving the simulated drives. Participants were instructed to drive as they usually would during the drives and provide verbal protocols throughout.

Within each drive, the participant drove continuously through a rural setting and encountered five rail level crossings of the same design (i.e. either the standard active crossing or the EID crossing). Each drive was approximately 11.5 km long, taking participants approximately 15 minutes to complete. The road and landscape features within the drive were designed to be identical, apart from the rail level crossing design. The five level crossings were spaced at regular intervals through the drive. Participants experienced the rail level crossing design twice with a train present and three times with no train. When a train was present, it began its approach to the crossing from an initial starting distance of 400 m from the rail level crossing, when participants were at a distance of 450 m from the rail level crossing. This was timed to ensure that participants would have peripheral vision of the train approaching, and would not reach the crossing prior to the train's arrival. The first rail level crossing encountered by the participant was always in an inactive (train-absent) state, with the order of subsequent train-present and train-absent exposures counterbalanced between drives. Drive order was fully counterbalanced between participants.

3.2.4 Data analysis

Two types of measures were used to evaluate the EID design in this study: mean speed on approach and decision-making.

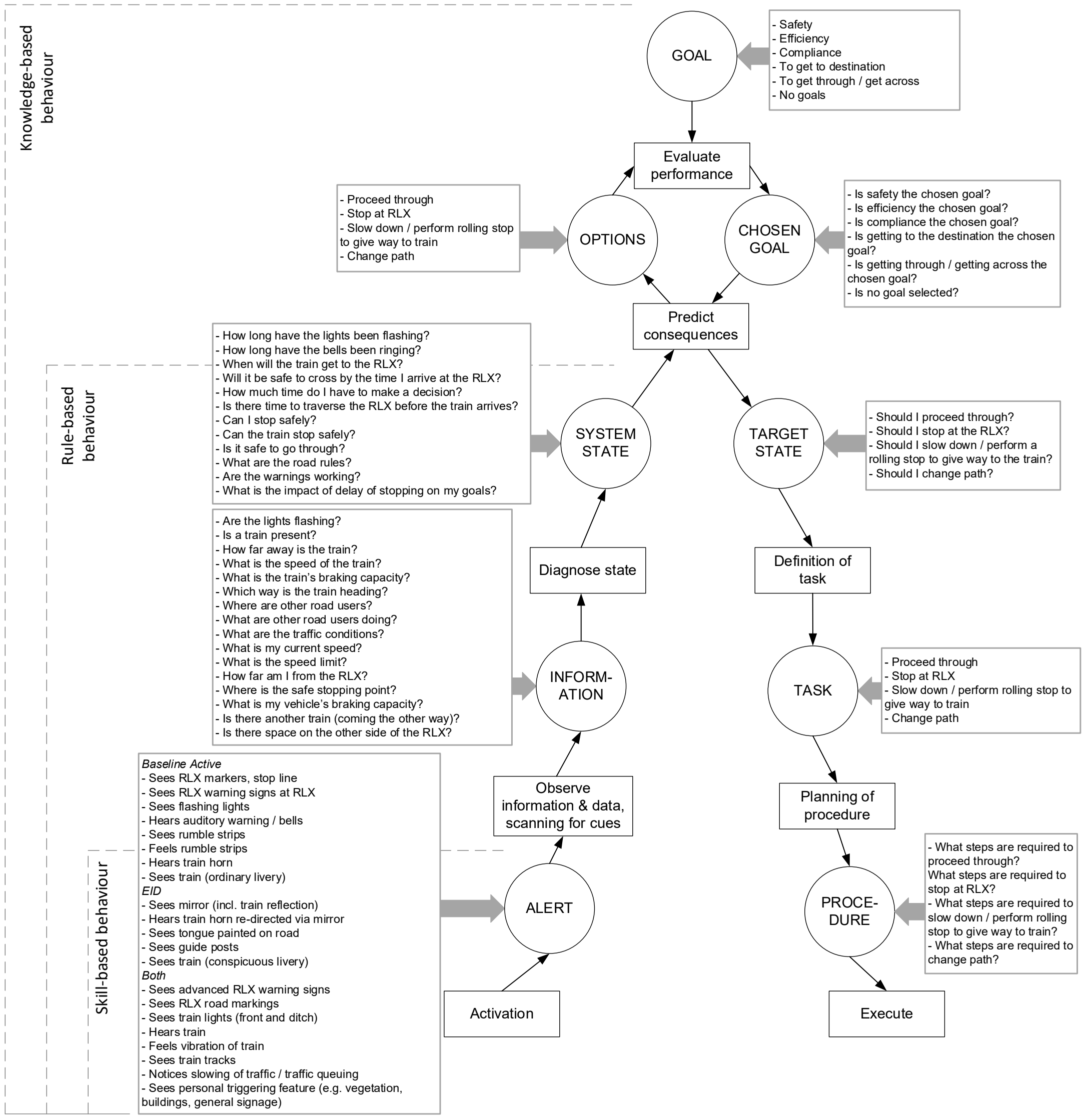
Mean speed on approach. Mean speed was analysed by averaging speed across 10m intervals, beginning 250m before the crossing and ending 10m after. Analyses were conducted in SPSS. Statistical significance was evaluated using an alpha level of .05. Greenhouse-Geisser degrees of freedom adjustments were applied where Mauchly's test indicated that the assumption of sphericity was violated.

Mean speed was analysed separately for train-present and train-absent encounters, as it was expected that most participants would stop in the presence of a train and therefore there would be large main effects of train presence. For each condition, mean speed was analysed using a 2 (crossing design: standard, EID) x 26 (distance: in 10m intervals from 250m before the crossing to 10m after) repeated-measures analysis of variance (RM-ANOVA).

Influence of key constraints on decision-making. The audio recordings of participants' concurrent verbal protocols were transcribed, and the verbalisations allocated to three approach zones: 250m to 150m, 150m to 50m and 50m to 10m past the crossing.

A generic decision ladder developed in previous research (Salmon et al. 2016) was adapted to understand how participants could undertake the stop or go decision when encountering the standard active design and the EID design (see Figure 4). Decision ladders outline the information processing activities (represented by boxes) and resultant knowledge states (represented by circles) that, if followed from the bottom left to the bottom right of the ladder, represent novice decision-making (Vicente, 1999). As expertise develops, shortcuts (leaps and shunts) can occur which means that individuals progress through the decision ladder without going through each information processing activity and experiencing every knowledge state. As shown at the left side of the figure, progression through the decision ladder can be used to indicate application of skill-based, rule-based, or knowledge-based behaviour (McIlroy & Stanton 2015a).

Figure 4. Generic decision ladder for the stop or go decision (adapted from Salmon et al. 2016)



Participants' concurrent verbal protocol data were mapped onto this generic ladder to understand patterns in decision-making at the crossings. In this study, the concurrent verbal protocols were analysed for participants' first train-present exposure and first train-absent exposure at each crossing.

Three analysts (GR, EG, PS) agreed on a set of rules for the decision ladder coding, a set of definitions for the elements of the decision ladder, and applied these to 10% of the data. One analyst (GR) then applied the agreed rules to the remainder of the data.

The rules included that:

- Only one alert per participant (the first verbalised by the participant) be identified.
- Information elements verbalised after verbalisation of the task to be undertaken / task execution not be identified on the decision ladder.
- Goals were only identified where a participant explicitly referred to a concern about being safe, efficient, compliant, etc. Goals were not inferred by lower level statements; for example, the statement “I’m just going to go through” was judged as not implying an efficiency goal.

An example of the rules applied to a verbal protocol transcript for one participant, for an encounter of the EID crossing when a train was present, is provided below. The coding is shown in square brackets:

> “Markings on the road [*Alert – Sees RLX road markings*]. Can hear the train… Decrease speed, allow the train to pass through [*Information – Is a train present?*], there’s a car at the other side [*Information – What are other road users doing?*]… Checking again for trains, nothing coming [*Information – Is another train coming?*], accelerate through, passing a car, looking at the road markings. Noticing the white posts on the side.” [*Shortcut taken: Information to Execute*]

> “Train approaching [A*lert – Sees train*] so slowing down. Can hear train, train approaching [*Information – Is a train present?*]. Car on opposite side, braking and slowly rolling towards intersection [*Information – What are other road users doing?*]. Train sign flashing *Information – Are the lights flashing?*] now stopped [*System state – Is it safe to go through?*]. So I’ll go through intersection [*Task – Rolling stop*] hopefully safely [*Goal – Safety*].”

Concurrent verbal protocols focus predominantly on cognitive processes rather than actions, therefore participants did not consistently verbalise the actions they executed as a result of decision-making. Therefore, objective speed data collected during the study were used to categorise the action executed by each participant within the decision ladder. Here, the minimum speeds of each participant were analysed from 250m on approach to the crossing. The categorisation adopted was defined as:

- Stop: Minimum approach speed of < 1km/h
- Rolling stop: Minimum speed of ≥ 1km/h, and < 10km/h
- Slow to give way to train: Minimum speed of ≥ 10km/h, and < 40km/h
- Proceed: Minimum speed of ≥ 40km/h

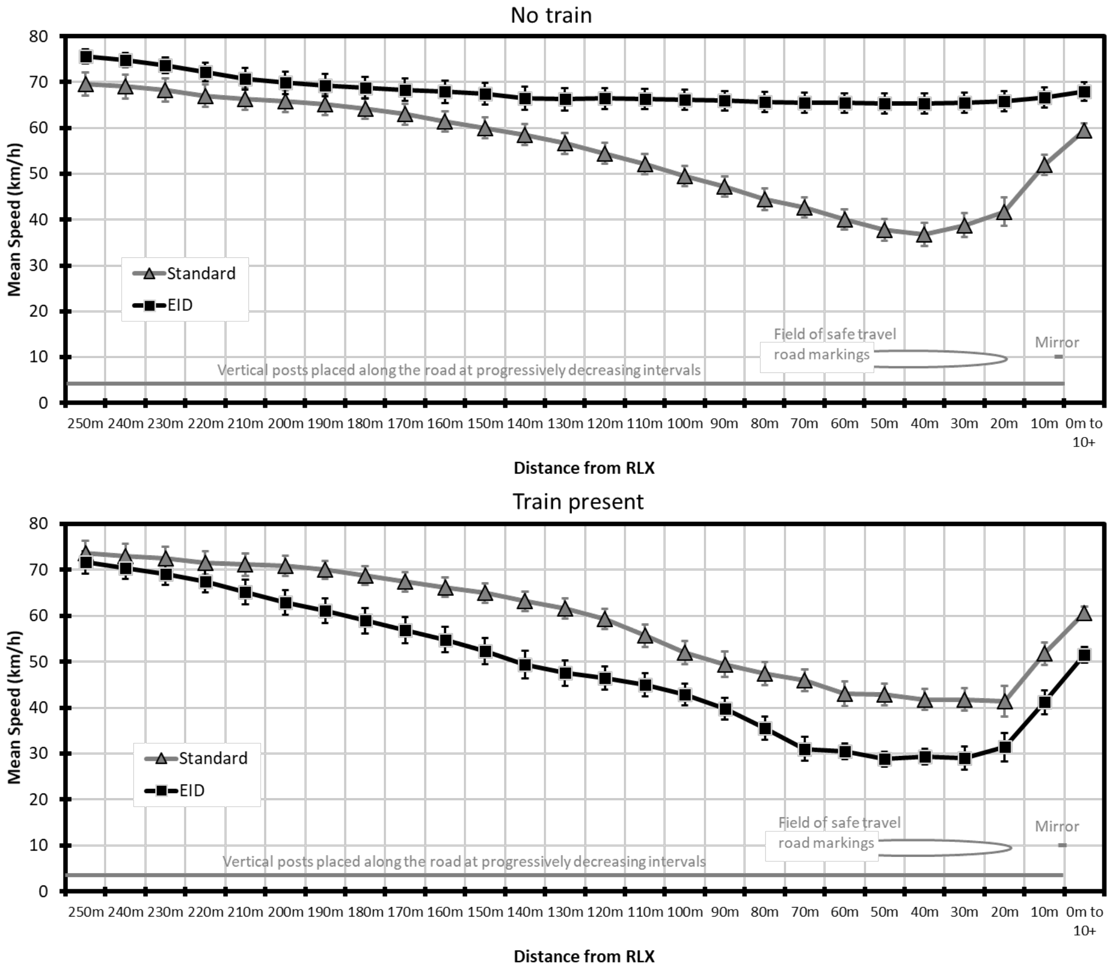
3.3 Results

3.3.1 Mean speed on approach

When analysing mean speed for the train-absent conditions, there were significant main effects of both crossing, $F(1, 29) = 58.05$, $p < .001$, $\eta_p^2 = .67$, and distance, $F(3.0, 88.4) = 37.46$, $p < .001$, $\eta_p^2 = .56$, as well as a significant crossing*distance interaction, $F(3.1, 88.5) = 17.47$, $p < .001$, $\eta_p^2 = .38$ (Greenhouse-Geisser adjusted degrees of freedom reported for distance main effect and interaction). Overall, when no train was present, mean speeds were significantly faster on approach to the EID crossing (*M* = 68.1 km/h, *SE* = 2.0, 95% CI [63.9, 72.2]) compared with the standard crossing (*M* = 55.1 km/h, *SE* = 1.4, 95% CI [52.3, 57.9]). Mean speed decreased steadily on approach, from a maximum of 72.6 km/h (*SE* = 1.7, 95% CI [69.1, 76.1]) during the period 250-240m before the crossing, to a minimum of 51.1 km/h (*SE* = 1.7, 95% CI [47.5, 54.6]) during the period 40-30m before the crossing. After this point, mean speed increased again, reaching 63.7 km/h (*SE* = 1.6, 95% CI [60.4, 67.0]) immediately after the crossing. As shown in Figure 5, the extent of speed reduction differed between crossings. On approach to the EID crossing participants slowed by only about 10 km/h, from a maximum of 75.7 (*SE* = 1.5, 95% CI [72.6, 78.7]) to a minimum of 65.3 km/h (*SE* = 2.2, 95% CI [60.7, 69.9]). In contrast, on approach to the standard crossing drivers slowed by more than 32 km/h, from 69.5 km/h (*SE* = 2.6, 95% CI [64.3, 74.8]) to 36.8 km/h (*SE* = 2.5, 95% CI [31.7, 41.8]).

Although drivers were consistently slower on approach to the standard crossing, the greatest differences were observed in the last 150m on approach to the crossing (see Figure 5).

Figure 5. Mean speed on approach to the crossing, by crossing design, with no train (upper panel) and train present (lower panel). Error bars represent ±1 standard error of the mean. Positions of key features of the EID design are shown in grey.



When analysing mean speed for the train-present conditions, once again there were significant main effects of crossing, $F(1, 29) = 67.28$, $p < .001$, $\eta_p^2 = .70$, and distance, $F(2.6, 74.1) = 50.03$, $p < .001$, $\eta_p^2 = .63$, as well as a significant crossing*distance interaction, $F(3.4, 97.5) = 3.13$, $p = .024$, $\eta_p^2 = .10$ (Greenhouse-Geisser adjusted degrees of freedom reported). However, the pattern was very different to in the train-absent conditions. When there was a train present, overall mean speeds were significantly *slower* on approach to the EID crossing (M = 48.8 km/h, SE = 1.4, 95% CI [45.9, 51.7]) compared with the standard crossing (*M* = 58.7 km/h, *SE* = 1.3, 95% CI [56.1, 61.3]). Again, mean speeds decreased on approach, with the maximum speed occurring 250m before the crossing for both designs. Participants displayed a greater extent of slowing on approach to the EID crossing, compared with the standard crossing (see Figure 5). Specifically, on approach to the EID crossing participants slowed from 71.6 km/h (*SE* = 2.5, 95% CI [66.6, 76.6]) to 28.8 km/h (*SE* = 1.6, 95% CI [25.5, 32.2]) during the period 50-40m before the crossing. In contrast, on approach to the standard crossing participants slowed from 73.5 km/h (*SE* = 2.8, 95% CI [67.9, 79.2]) to 41.4 km/h (*SE* = 3.3, 95% CI [34.7, 48.2]) during the period 20-10m before the crossing.

3.3.2 Influence of constraints on decision-making

To understand decision-making under normal conditions, the generic decision ladder was overlaid with the verbal protocol data from Study 1. The results of the decision ladder mapping are shown in Figure 6.

When no train was present, only a small number of *Alerts* were used within the EID design to become aware of the need to make a stop or go decision, with most participants verbalising no alerts. In comparison, the rumble strips and advanced warning signs appeared to be salient alerts for many participants when encountering the standard design. In considering the *Information* used by participants, the majority of participants encountering both designs were clearly concerned with whether a train was present (87% when encountering the standard, 90% when encountering the EID crossing). From the information gathering stage, many participants then exhibited short cuts in their decision-making. For the EID crossing, 57% exhibited a short cut to defining the task they would undertake, while 37% simply executed the determined action to proceed, stop, perform a rolling stop or slow and then proceed. The remaining two participants did not exhibit a short cut from the left-hand side to right hand side of the decision ladder, engaging in knowledge-based behaviour. For the standard design, there was a slightly different pattern, with participants appearing to be operating more at the lower levels of the decision ladder. Here, all participants used short cuts with the majority (53%) moving between *Information* and *Execution*, while 43% first defined the task they would undertake, before moving to task execution. In relation to the actual tasks executed when no train was present, based on minimum speeds for each participant on each approach, there was little difference between the two designs, with most participants proceeding through the crossing.

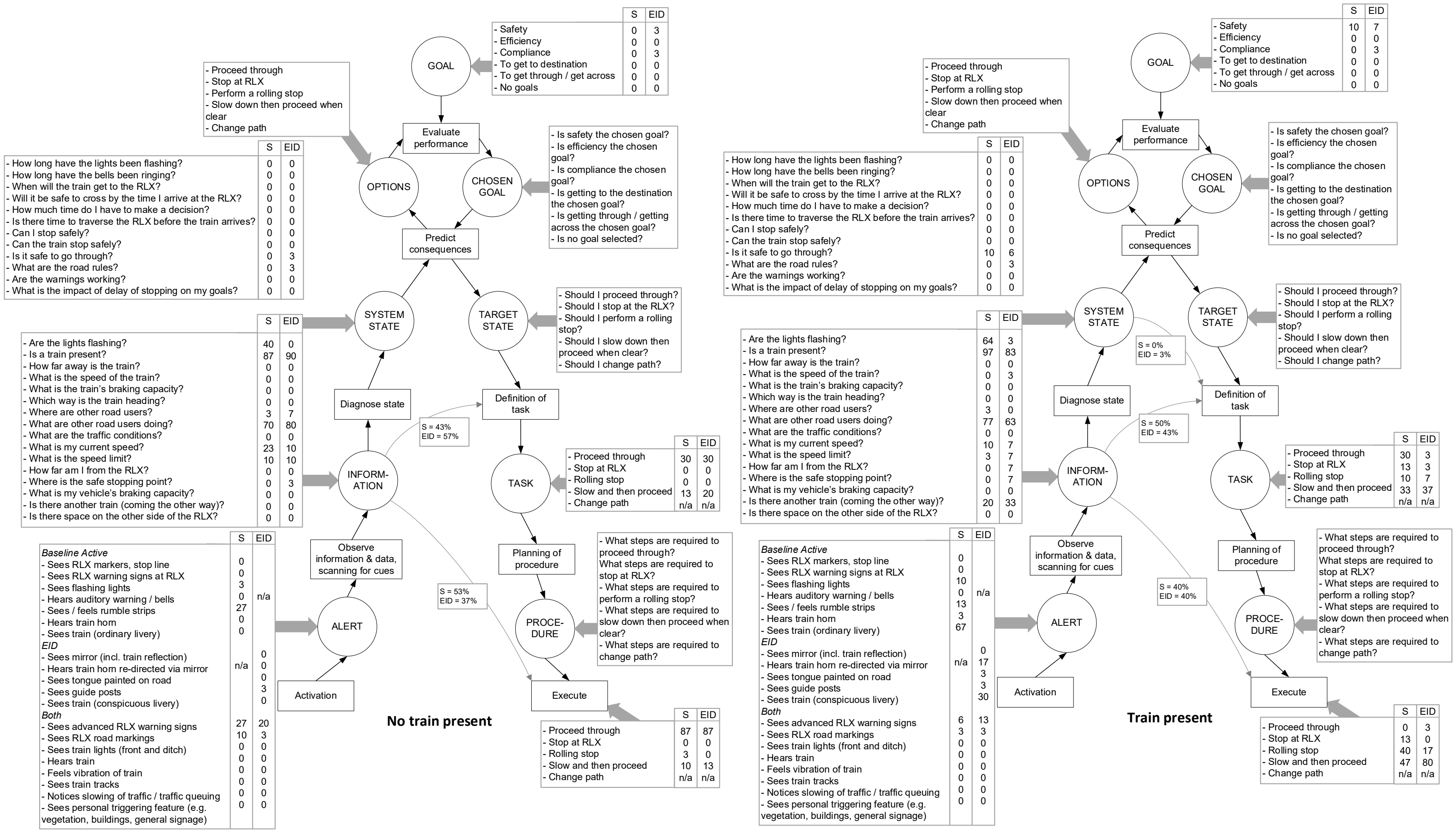
Overall, with no train present, participants were more likely to engage in more effortful decision-making (i.e. move further up the decision ladder) when faced with the EID crossing than the standard crossing.

When a train was present, seeing the train was the most commonly identified *Alert* mentioned by 30% of participants when encountering the EID design and 67% when encountering the standard design. Interestingly, 17% of participants used the sound of the train as the alert when encountering the EID design, but no participants used this alert in the standard design. The rumble strips and flashing lights also acted as *Alerts* for the standard crossing, but not for the EID design as they were not present. In terms of *Information*, most participants were concerned with whether a train was approaching. Nearly all participants (97%) considered the train's presence when encountering the standard crossing, while this was slightly less frequent for the encounters with the EID design (83%). As with the no train condition, most participants exhibited short cuts in their decision-making. For the EID design, 43% of participants moved from *Information* to *Definition of the task*, and 40% from *Information* to *Execution*. One participant moved up from *Information* to consider the *System state*, then to *Definition of task*. The remaining four participants (14%) did not exhibit a short cut from the left side to right side of the decision ladder, and could be considered to be engaging in knowledge-based behaviour. With the standard design, half of participants (50%) moved from *Information* to definition of task, and 40% directly from *Information* to *Execution*. The remaining three participants did not exhibit short cuts from the left hand to right hand side of the decision ladder.

In relation to the actions executed by users with a train present, participants were less likely to stop (0% versus 13%) or come to a rolling stop (17% versus 40%) in response to the EID design, compared with the standard.

Overall, when a train was present, across both crossings most participants appeared to follow a rule of: if train is present, execute action to either slow and then proceed or perform a rolling stop.

Figure 6. Decision ladders of participant decision-making when encountering the standard (S) and EID designs under train-absent and train present conditions. Note, figures are percentages of participants.



4. STUDY 3: EVALUATION UNDER NON-OPTIMAL CONDITIONS

4.1 Study design

A within-subjects design whereby each participant experienced both the EID and standard active design was used to compare driver responses to the designs under non-optimal conditions of distraction and technology failure. Within the study participants also experienced three other rail level crossing designs, however this analysis reports only the results for the EID and standard active crossings. Each drive included four rail level crossing encounters of the same type (either EID or the active standard), which operated identically to Study 2, but were experienced under conditions of in-vehicle distraction and technology failure, in addition to normal conditions.

In-vehicle distraction. A visual detection task was used to evaluate the influence of in-vehicle distraction. The task required participants to immediately press a button on the steering wheel whenever they detected a small red dot that appeared at the bottom of the centre screen of the simulator at pseudo-random intervals. Once the distractor was acknowledged, it disappeared from the participant's view. Similarly designed tasks have been found to induce distraction-related errors in real driving (e.g., Young et al. 2013). During each drive there were five occasions where the distractor was presented: twice when the participant was driving on a straight section of road, not on approach to a rail level crossing; twice when the participant was negotiating a curve or a corner; and once when the participant was on approach to the rail level crossing (with no train approaching). The current analysis focusses on performance on approach to the rail level crossing.

System failure state. The system failure state involved participants experiencing each rail level crossing design in a situation where there was a train approaching and warnings were unavailable or functioning in a suboptimal manner. Participants were not informed that failure states would be encountered to avoid priming them to search for failures, which are rare events in real world conditions.

Because each design included unique warnings, each had a unique failure state, based on plausible real-world technology failure scenarios. Rail industry stakeholders indicated that technical issues can involve complete failure (i.e., no warning), but more commonly involve late train detection by the technical system resulting in delayed warnings (i.e., full warning time not provided). Therefore, for the standard active crossing, the failure state involved delayed warning activation, with the flashing lights and bells triggered 15s later than normal. Australian standards specify a minimum warning time of 25s, so this represents a substantial delay. During the design process, it was noted that the EID crossing mirrors may be subject to vandalism, so the EID fail state involved vandalism, with the mirrors depicting the approaching train being defaced by graffiti (thus obscuring vision of approaching trains).

4.2 Method

4.2.1 Participants

Participants were 25 drivers (8 male) with an average of 15.0 years' driving experience (*SD* = 11.2). All participants were experienced, fully-licensed drivers who provided written informed consent and received financial reimbursement for their time. The participant sample was independent of Study 2 (i.e. no participants were involved in both studies). Ethical aspects of the research were approved by the University of the Sunshine Coast Human Research Ethics Committee (approval number A/15/756).

4.2.2 Apparatus

The same apparatus used in Study 2 was used in this study.

4.2.3 Procedure

The same general procedure as used in Study 2 was adopted in this study, with the exception of the conditions experienced. The four conditions experienced by participants in each drive were:

- No train approaching, normal conditions.

- Train approaching, normal conditions.
- No train approaching, in-vehicle distraction.
- Train approaching, technology failure state.

The first crossing in each drive was the normal train-present condition, to expose participants to the design in its normal active state. The order of other encounters was counterbalanced between conditions. The order of experimental drives was counterbalanced between participants.

4.2.4 Data analysis

Three types of measures were used to evaluate the EID design in this study: mean speed on approach; decision-making; and reaction time to the distractor.

Mean speed. As with Study 2, mean speed was analysed by averaging speed across 10m intervals, beginning 250m before the crossing and ending 10m after. Two analyses were conducted: one evaluating the effects of distraction and one evaluating the effects of technology failure. The distraction analysis involved a 2 (crossing) x 2 (condition: non-distracted, distracted) x 26 (distance) RM-ANOVA, including only train-absent encounters. The technology failure analysis involved a 2 (crossing) x 2 (condition: normal, failure) x 26 (distance) RM-ANOVA, including only train-present encounters.

Influence of constraints on decision-making. As in Study 2, participants' concurrent verbal protocol data were mapped onto the generic decision ladder (Figure 3) to understand patterns in decision-making at the crossings. In this study the verbal protocols were analysed for the exposure to the distractor at each crossing (occurring in a train-absent encounter) and the technology failure at each crossing (occurring in a train present encounter).

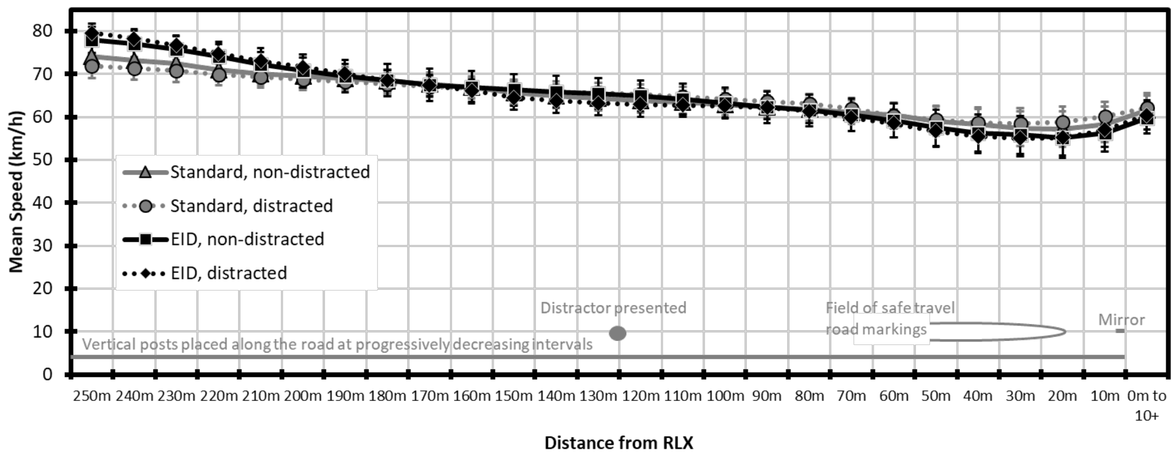
Performance under distraction. Distractor reaction times were compared using a Wilcoxon Signed Rank Test because Shapiro-Wilk tests indicated the data were not normally distributed. Reaction time values were removed from the dataset if the participant failed to respond, or if the value exceeded 4s. This resulted in reaction time data for one participant being excluded from the analyses.

4.3 Results

4.3.1 Performance under distraction

Mean speed on approach. The main effect of distraction on mean speed was not statistically significant, $F(1, 24) = 0.00$, $p = .974$, $\eta_p^2 = .00$, and distraction did not significantly interact with any of the other variables (all $F < 1$, $p > .7$, $\eta_p^2 < .03$). The main effect of crossing was not statistically significant, $F(1, 24) = 0.01$, $p = .943$, $\eta_p^2 = .00$, but there was a significant main effect of distance, $F(25, 600) = 26.04$, $p < .001$, $\eta_p^2 = .52$, and a significant crossing*distance interaction, $F(25, 600) = 3.66$, $p < .001$, $\eta_p^2 = .13$. As shown in Figure 7, mean speeds decreased on approach from a maximum of 75.8 km/h (*SE* = 1.9, 95% CI [71.9, 79.8]) 250m before the crossing, to a minimum of 56.5 km/h (*SE* = 3.8, 95% CI [48.7, 64.4]) during the period 20-10m before the crossing. After this point, mean speed increased slightly, reaching 61.0 km/h (*SE* = 3.2, 95% CI [54.5, 67.5]) immediately after the crossing. The extent of this reduction was larger for EID compared with the standard crossing, resulting in the significant interaction term. Specifically, mean speed on approach to EID reduced by nearly 24 km/h, from 78.8 km/h (*SE* = 2.4, 95% CI [73.9, 83.7]) to 55.2 km/h (*SE* = 4.2, 95% CI [46.4, 63.9]), whereas mean speed on approach to the standard crossing reduced by only 15 km/h, from a maximum of 72.9 km/h (*SE* = 2.5, 95% CI [67.8, 78.1]) to 57.9 km/h (*SE* = 3.7, 95% CI [50.3, 65.5]).

Figure 7. Mean speed on approach to the crossing, comparing distracted and non-distracted conditions for each crossing design. Note there was no train present in any of the encounters. Error bars represent ±1 standard error of the mean.

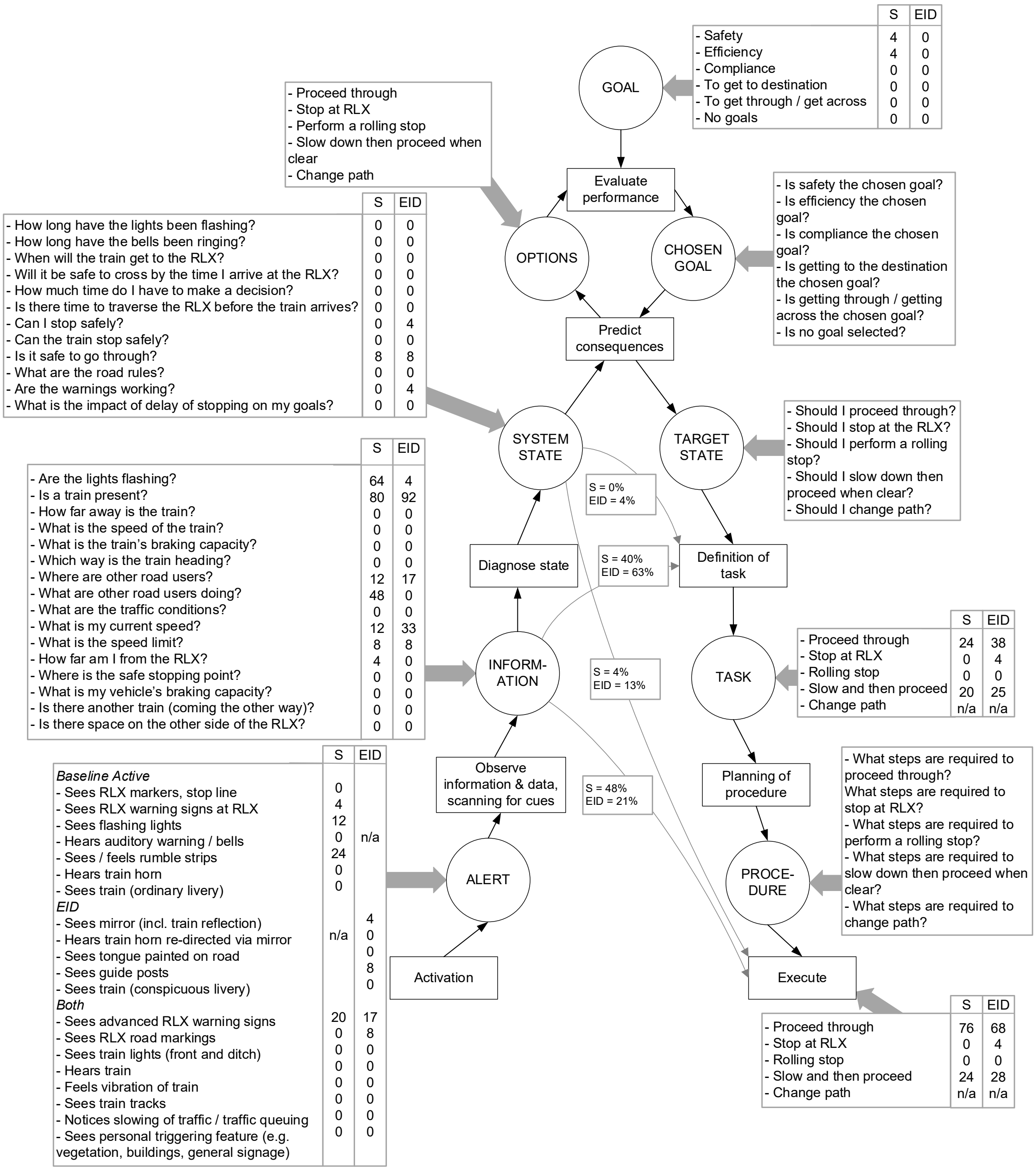


Influence of constraints on decision-making. Figure 8 compares decision-making for the two crossing designs under conditions of distraction. In relation to *Alerts*, there were few differences between the two designs that were unique to the distraction condition (i.e. that were not identified in the train-absent, normal conditions reported in Study 2). In relation to *Information*, participants more often considered the presence of a train (92% versus 80%), or their own speed (33% versus 12%), when encountering the EID design in comparison to the standard design. In the standard design, a large proportion of participants (48%) considered the actions of another road vehicle, while no participants mentioned this in the EID drive. This was an artefact of the simulation design whereby due to the counterbalancing the presentation of the distractor within the drives, in the standard drive it was presented at a crossing where another vehicle was present (approaching in the other direction) while in the EID drive it was presented at a crossing where no other vehicles were present. From the *Information* stage, most participants then exhibited short cuts in their decision-making. When encountering the EID design, 63% of participants moved from *Information* to *Definition of task*, and 21% directly from *Information* to *Execution*. One participant (4%) moved from *Information*, to *System state*, then to *Definition of task* and the remaining 13% of participants moved from

Information to *System state*, then to *Execute*. For example, one of the participants stated, “There doesn't seem to be a train approaching… Seems safe so I'm going to cross it.” When encountering the standard crossing 40% of participants moved from *Information* to *Definition of task*, while 48% moved directly from *Information* to *Execution.* One participant performed a short cut from *Information* to *System state*, then to *Execute,* and the remaining two participants (8%) did not exhibit any short cuts from the left-hand side to right hand side of the decision ladder.

In relation to the actions executed by users under conditions of distraction, most participants proceeded through or slowed and then proceeded. One participant encountering the EID crossing came to a stop at the crossing, although no train was present.

Figure 8. Decision ladder analysis comparing the designs under conditions of distraction. Note, S = Standard design (*n* = 25); EID = EID design (*n* = 24 due to missing data for 1 participant).



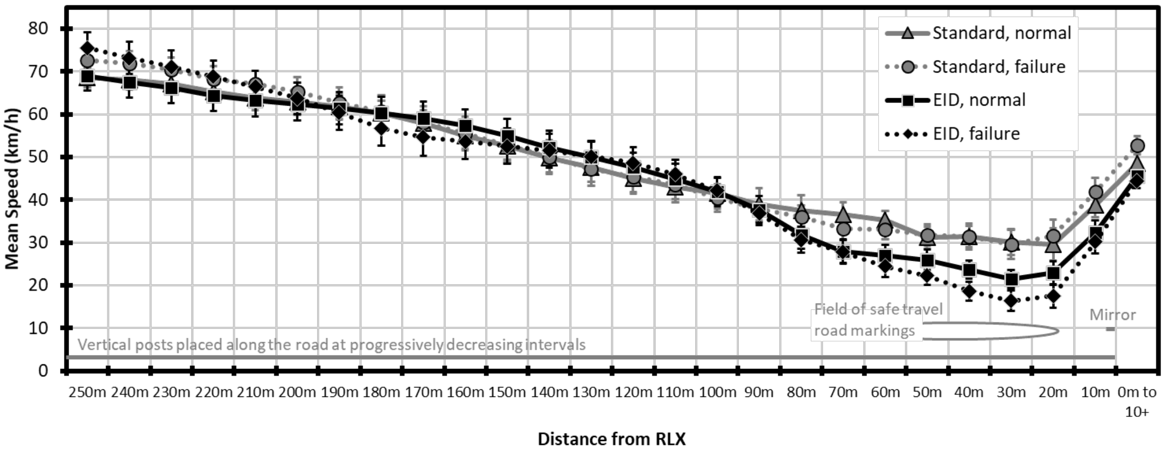
Reaction time. Distractor reaction times on approach to the two crossing types differed significantly between crossing designs, $Z = -2.148$, $p = .032$. Reaction times were slower when approaching the EID crossing ($M = 1.242$s, $SD = 0.349$, Mdn = 1.225) compared with the standard crossing ($M = 1.129$s, $SD = 0.453$, Mdn = 1.050).

4.3.2 Performance under failure conditions

Mean speed on approach. The main effect of technology failure on mean speed was not statistically significant, $F(1, 24) = 0.01$, $p = .922$, $\eta_p^2 = .00$, and failure did not significantly interact with any of the other variables (all $F < 1.25$, $p > .2$, $\eta_p^2 < .05$). As in Study 2, there were significant main effects of crossing, $F(1, 24) = 8.34$, $p = .008$, $\eta_p^2 = .26$, and distance, $F(25, 600) = 66.22$, $p < .001$, $\eta_p^2 = .73$, and a significant crossing*distance interaction, $F(25, 600) = 3.89$, $p < .001$, $\eta_p^2 = .14$. Overall mean speeds were slightly slower on approach to the EID crossing ($M = 46.6$ km/h, $SE = 1.9$, 95% CI [42.6, 50.6]) compared with the standard crossing ($M = 49.2$ km/h, $SE = 1.7$, 95% CI [45.7, 52.7]), although the difference was relatively small.

As shown in Figure 9, mean speeds when a train was present decreased on approach from a maximum of 71.4 km/h ($SE = 2.2$, 95% CI [66.9, 75.9]) 250m before the crossing, to a minimum of 24.4 km/h ($SE = 2.1$, 95% CI [20.0, 28.8]) during the period 30-20m before the crossing, and then increased to 47.8 km/h ($SE = 1.5$, 95% CI [44.7, 50.9]) immediately after the crossing. The extent of this reduction was again larger for EID compared with the standard crossing. Specifically, mean speed on approach to EID reduced by over 53 km/h, from 72.2 km/h ($SE = 2.7$, 95% CI [66.6, 77.9]) to 19.0 km/h ($SE = 1.9$, 95% CI [15.0, 22.9]), whereas mean speed on approach to the standard crossing reduced by approximately 40 km/h, from a maximum of 70.6 km/h ($SE = 2.2$, 95% CI [66.1, 75.1]) to 29.9 km/h ($SE = 3.0$, 95% CI [23.8, 36.0]).

Figure 9. Mean speed on approach to the crossing, comparing “technology failure” and normal (no failure) conditions for each crossing design. Note there was a train approaching the crossing in all encounters. Error bars represent ±1 standard error of the mean.

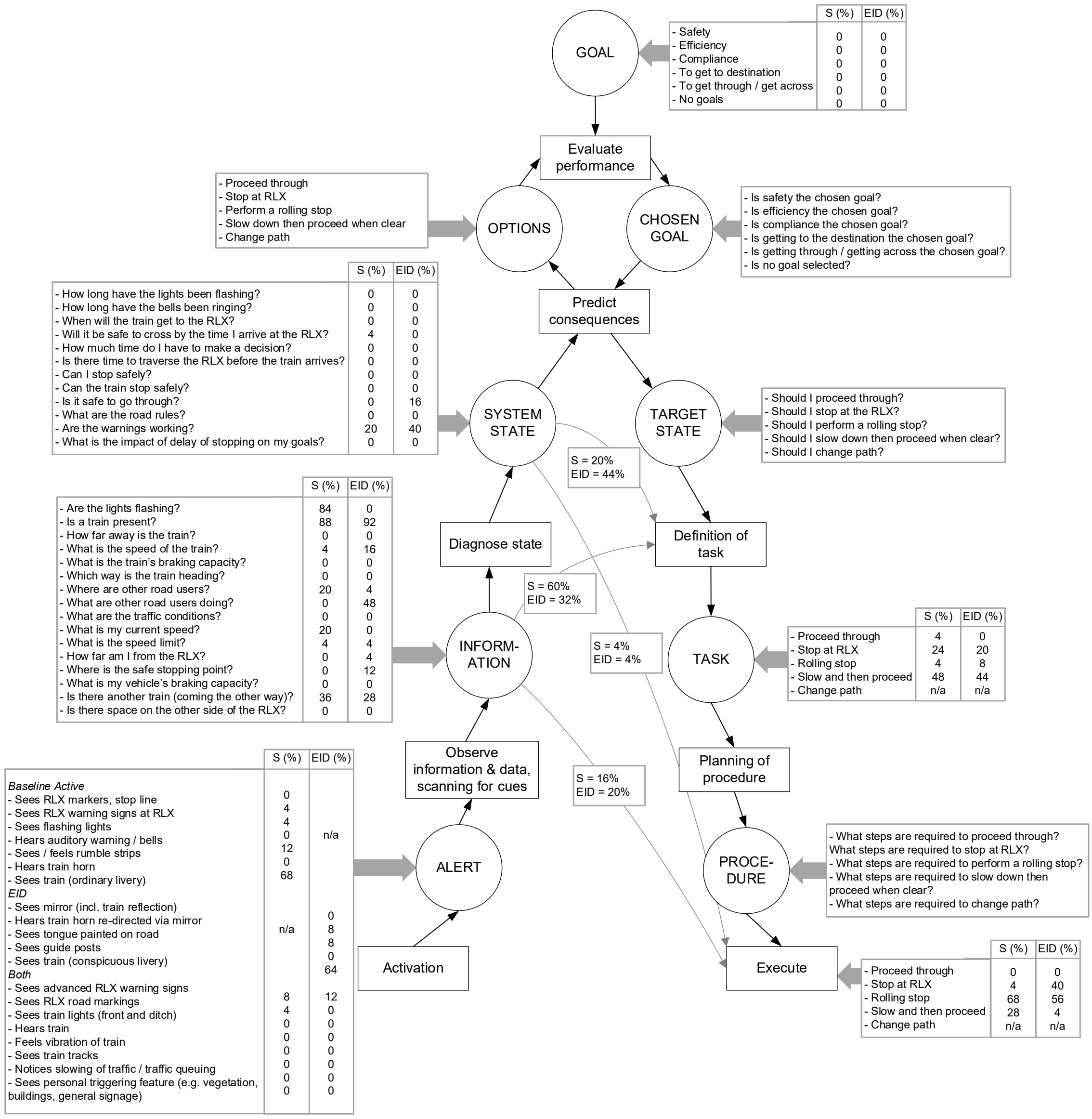


Influence of constraints on decision-making. Figure 10 compares decision-making for the two crossings under conditions of technology failure. In relation to *Alerts*, the findings were similar to those identified for the train present, normal conditions identified in Study 2. In relation to *Information*, more participants encountering the EID design mentioned the speed of the train (16% versus 4%), and the location of a safe stopping point (12% versus 0%), when compared to the standard crossing. When considering short cuts through the decision ladder, for both designs, participants engaged in decision-making at higher levels of the decision ladder. For the EID design, the largest proportion (44%) of participants moved between the *System state* (predominantly the consideration of “Are the warnings working?”), and then moved to defining the task to be undertaken. In contrast, for the standard design, the largest proportion (60%) of participants moved from *Information* (predominantly “Are the lights flashing” or “Is a train present”) to defining the task to be undertaken. Thus, most participants encountering the standard design did not diagnose the situation of a technology failure. In fact, only 20% of participants encountering the standard design in the failed state questioned whether the warnings were working, with comments such as “Wow that seems really late. OK, all looks good to go. I really didn't see the train then, it was terrible.”

Further, participants appeared to demonstrate more cautious behaviour when encountering the EID crossing, with 40% of participants coming to a stop at the crossing, versus 4% of participants stopping at the standard crossing.

Overall, under conditions of failure, participants encountering the standard design were less likely to engage with the higher levels of the decision ladder, in comparison to the EID design.

Figure 10. Decision ladder analysis comparing the designs under conditions of technology failure. Note, S = Standard design; EID = EID design; *n* = 25.



5. DISCUSSION

This paper has described the development and evaluation of a novel EID-based rail level crossing design. The aims were to investigate whether EID could be applied to the design of a physical road environment, and to compare driving performance at the EID-based design, compared to a standard active rail level crossing design.

In relation to the first aim, we were able to develop an innovative concept for a level crossing environment using the EID approach. Analysing the key constraints of the system helped to focus the design elements on the most important aspects, such as the train, and the speed of road and rail vehicles, rather than on traditional countermeasures used at rail level crossings such as warning signage and lights, that generally rely on symbolic representations of the hazard presented by an approaching train.

In relation to the evaluation of the EID design, under normal conditions, with no train present, participants slowed more on approach to the standard crossing than the EID, for which they generally maintained their speed. With a train present, mean speeds were slower on approach to the EID crossing, compared to the standard. Participants displayed a greater extent of slowing on approach, and reached their minimum speed earlier, compared with the standard crossing. This pattern indicates that the EID design produced speed behaviour contingent on the situation. Participant behaviour was more responsive to the presence or absence of a train at the EID crossing compared to the standard design. This may have been supported by participants being more likely to engage in more effortful decision-making (i.e. move further up the decision ladder) when encountering the EID crossing compared to the standard crossing. These findings suggest that there may be both efficiency and safety benefits of the design, with drivers encountering the EID design slowing less with no train present, and slowing more when a train is present.

Under conditions of distraction, there was little difference in the speed profiles of the two designs, although participants encountering the EID crossing did slow significantly more on approach than when encountering the standard design. Further, reaction times to the distractor were significantly longer when encountering the EID to the standard design. Participants may have self-regulated their response to the distractor, focussing on the driving task and allowing performance to degrade in the secondary task (distractor response). This may explain why they slowed more when approaching the EID design. Given the higher uncertainty and unfamiliarity with the environment, using a slower and more cautious speed on approach can be considered a safety-promoting behaviour. Participants also engaged in more deliberate decision-making at the EID crossing when under conditions of distraction. Their decision-making patterns also suggested that a strong focus on the train as a constraint was maintained, more so than in the standard design.

Under conditions of technology failure, participants again slowed more in response to the EID crossing. Of note, 40% of participants stopped at the EID crossing when it was in a failed state, compared with only 4% of participants encountering the standard design. However, no participants proceeded through in front of the on-coming train.

Participants were also more likely to engage in higher level cognitive processing when faced with the EID crossing in a failed state, compared to the standard crossing. This may suggest that participants were over-reliant on the flashing lights at the standard active crossing; applying simple rules such as stopping (or coming to a rolling stop) when the lights are flashing. Application of such rules, supported by existing designs, can have disastrous consequences in the real world. For example, in the level crossing collision at Kerang in Victoria, Australia, in which seven people were killed when a truck struck a passenger train at a rural rail level crossing, the truck driver had stated that he looked at the level crossing warning lights but had not perceived that they were flashing. An analysis by Salmon and colleagues (2013) suggested that the truck driver had experienced a 'looked-but-failed-to-see' error. Had the driver been induced by the design to engage in higher level cognitive processing, such an error might have been less likely to occur.

5.1 Limitations and future research

As the evaluation of the EID crossing was conducted using driving simulation, there were some limitations regarding the representation of the crossing environments. First, due to the lack of environmental complexity in the simulator, the approaching train may have been a more salient cue than it would have been in the real world. Second, it was difficult to simulate the mirror within the EID crossing design. Potentially, a real world, physical rendering of this concept would provide greater benefits to road users. Similarly, recognition of failure modes may be more obvious in a real world environment than in the simulator. Regardless, before any recommendations could be made regarding implementation of the design in practice, field trials would be required to understand driver behaviour in a real-world environment.

Another potential limitation is that the EID design was novel to participants, and thus it is unknown whether behaviour in response to the design would change over time as familiarity increases. This could be addressed through future research, such as simulation studies in which participants are exposed to the crossing over a large number of trials.

Finally, while the EID crossing design incorporated features to influence train driver behaviour, such as the lowered speed, we did not evaluate the effects of these. For example, whether the design would create unacceptable delays on the rail network. Further research should consider the impacts on the train driver and rail network, as well as other end users such as truck drivers, cyclists and motorcyclists. Such research should also consider any contextual differences such as differing road vehicle and train speeds, or different road rules, that apply in different locations or across different countries.

6. CONCLUSION

This paper has described a first of its kind level crossing concept, designed using the EID approach. The evaluation of the design, using driving simulation, demonstrated more favourable behaviours than the existing active design. Importantly, drivers were more likely to stop at the EID crossing during the technology failure condition. The evaluation also provided insight into decision-making at rail level crossings and showed that the EID design tended to promote decision-making at a higher level of cognitive control than the existing standard design. Beyond the evaluation of this particular novel design, the findings suggest that consideration should be given to designing RLX and high-risk road safety infrastructure in a way that induces users to engage in more effortful, conscious decision making, and assists road users to respond appropriately in situations of uncertainty by ‘finishing the design’. Future research should seek to examine whether these positive effects of the EID concept can be transferred over into the real world.

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